Image Thickness Correction for Navigation with 3D Intra-cardiac Ultrasound Catheter

Hua Zhong[1], Takeo Kanade[1], and David Schwartzman[2]

[1] Computer Science Department, Carnegie Mellon University, USA,
[2] University of Pittsburgh Medical Center, USA.

Abstract. In this paper we present an algorithm to correct 3D reconstruction errors of 3D ultrasound catheter caused by ultrasound image thickness. We also provide a easy way to quickly measure ultrasound image plane's thickness. With our thickness correction 3D reconstruction, registration accuracy of navigation system using 3D ultrasound catheters can be greatly improved.

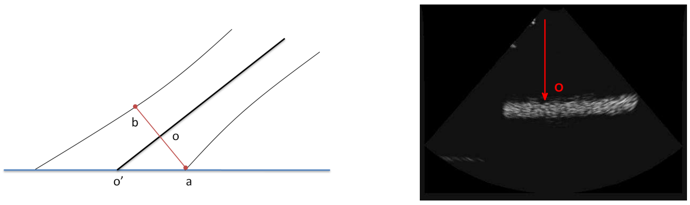
1 Introduction

Recent years, many navigation systems are developed for minimally invasive heart surgery. In the past few years, both research systems [1] [2] and commercial available system (Carto Merge from Biosense Webster) use position sensor tracked catheters to touch heart walls at several locations during an operation and register them with pre-operative high resolution images to enable instrument navigation. Some recent navigation system [3], employees an ultrasound catheter to quickly scan heart wall and reconstruct 3D heart surfaces points during an operation and register them with pre-operative CT scans. Such system can greatly improve the speed (hundreds of times faster has been claimed) and reliability of collecting intra-operative surface data for registration.

To reconstruct 3D heart surface points, this system uses simple edge detection algorithm to find first edge pixel in ultrasound images from transducer's center corresponding the first reflected sound. With a position sensor on the ultrasound catheter 3D coordinates of those pixels can be computed. This method assumes ultrasound image plane is infinitely thin but in reality ultrasound image plane has thickness.

1.1 Error Caused by Image Plane Thickness

Figure 1 (a) shows an ultrasound image plane (bold black line) with finite thickness (thin black lines) intersect an object surface (horizontal blue line). Because the image plane is not perpendicular to the object surface, at point a, part of the image plane first hits the object surface and reflects some ultrasound energy. o' is where the center image plane hits the object surface and reflects energy. Eventually, the object surface in ultrasound image will be a wide band (Figure 1 (b)), *not* an infinitely thin line as it should be with zero thickness image plane. In this case, if we just detect the first edge pixel from the transducer in ultrasound image (represents the first reflection of sound waves) as where the surface is, o will be taken as a point on the object surface while the real 3D point on the object surface should be a. This error is proportional to the ultrasound image plane's thickness at the depth o. Thickness of an intra-cardiac ultrasound catheter's image plane ranges from 3 to 6mm. Navigation error acceptable to doctors is around 2mm or less. Such error cause by thickness of image plane has been observed[4].



(a) (b)

Fig. 1. Surface intersect with ultrasound image plane with finite thickness

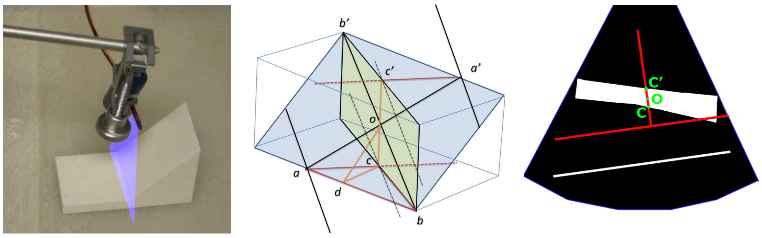
To address such error from ultrasound image plane thickness, we first propose a method to measure the thickness of an ultrasound image plane in section 2. And we provide an algorithm to correct 3D surface points errors with measured thickness information (section 3) and register (section 3.2) the corrected points with pre-operative 3D heart surface models. A phantom model test and its result analysis will be presented in section 4 to verify the improvement with our algorithm.

2 Ultrasound Image Thickness Measurement

Thickness of ultrasound image plane is also called the ultrasound beam width. It is not uniform everywhere and can be thought as a function of depth (distance from the ultrasound transducer). It can be measured by carefully built phantom models [5][6]. The basic idea is to intersect the ultrasound image plane with a flat surface at 45 degree angle. In that case, the width of the band in ultrasound image equals to the thickness of the image plane at the depth. Then either move the ultrasound transducer up and down or use multiple parallel surfaces to measure the distance at different depth. To precisely measure image thickness those methods need carefully built models and accurate movement of transducers. In this paper we reduce many restrictions of those methods to as simple as a single slope surface with any angle (0-90) to a flat water tank bottom and give a general formula to measure the thickness of an ultrasound image.

2.1 Phantom Model Setup

Our method requires only a single slope on a flat surface (a flat water tank bottom will do) as shown in Figure 2 (a). Our model has an extended flat surface only because the material of our model has a better visibility in ultrasound than the water tank bottom. There is no restriction to the slope's angle α.



(a) (b) (c)

Fig. 2. Measure thickness of an ultrasound image plane

We use a clamp to hold the ultrasound catheter (Figure 2 (a) highlighted by red lines) so that the ultrasound image plane (blue plane) is perpendicular to the water tank bottom. It can be verified by rotating the catheter along its proximate direction, when the white band in ultrasound image generated by the tank bottom is at its thinnest, the image plane is perpendicular to the tank bottom. The thin straight line in ultrasound image representing the water tank bottom is called our "*reference line*". Later we will need it to compute thickness.

Now we slide the slope into the image plane. As we move the slope back and forth, the white band representing the slope surface should sweep across the ultrasound image at different depth. Here we need to sweeps most part of the ultrasound image multiple times to make sure we have enough samples.

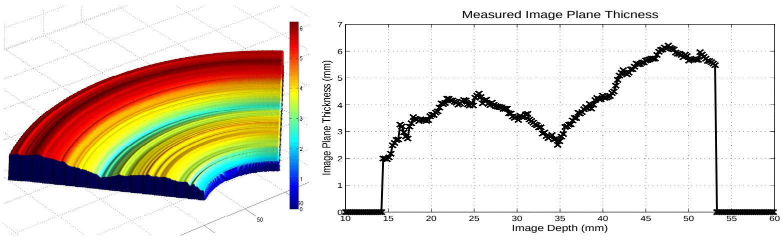
2.2 Compute the Thickness Function

For an ultrasound image, the image plane intersects the sloped surface and generate a wide band in it. As shown in Figure 2 (b), blue plane $aba'b'$ is the slope and yellow plane $bcb'c'$ is the center of the image plane. Because the image plane has a finite thickness, it hits the slope from a' to a. Their projection on the center of the image plane are c and c'. Figure 2 (c) is the corresponding ultrasound image. The white band is the reflection from the slope surface. The thin white line is the reference line (tank bottom). It is perpendicular to the image plane. c, c' and o correspond to the same point in Figure 2 (b).

Given that $ac \perp bcb'c'$, $cc' \perp bc$ and bc is parallel to the reference line, we draw a line cd in plane abc so that $cd \perp ad$, then $od \perp ab$. So $\angle odc$ is the slope's angle α which can be measured. $\angle obc$ is the angle between reference line and the center line of the white band generated by slope surface. It can be measured in ultrasound image. We call it β. cc' is the width of the white band along the direction perpendicular to the reference line, which can be measured. We call it w. Then oc is $\frac{w}{2}$. ac is half of the thickness of image plane at point o. With all the perpendicular relations mentioned above, we can get:

$$Thickness = w \cdot \frac{1}{\sqrt{tg^2\alpha - tg^2\beta}} \tag{1}$$

Previous methods are special cases of our method which have $\alpha = 45$ and $\beta = 0$. Then Equation (1) becomes $Thickness = w$. We use Equation (1) to compute the thickness for each ultrasound image sampled at various depth. For depth with no samples, we can interpolate its thickness with neighboring samples. Then a continuous thickness function $Thickness = f(depth)$ can be reconstructed. Figure 3 shows the result we have for the ultrasound catheter used in our experiment. The middle range with least thickness is the focus region of the image plane. As depth decreases and increases from the focus region, thickness increases.



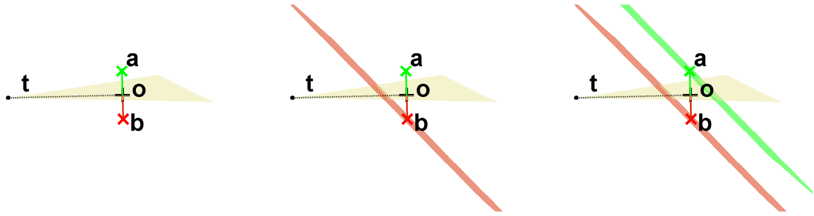
(a) (b)

Fig. 3. Measured thickness of ultrasound image plane. (a) 3D visualization of the thickness of an ultrasound image. (b) The thickness function we measured. X-axis is depth (distance from transducer) and Y-axis is thickness (beam width). Depth with zero thickness means no sample has been captured at that depth.

3 Image Thickness Correction for Registration

3.1 Correction of Error from Image Thickness

Figure 4 (a) shows an ultrasound image plane (yellow surface) with first edge point from transducer at o and transducer's center at t. With 3D ultrasound catheter, we know the normal of ultrasound image plane and 3D coordinate of t. There are two possible object surface point which can generate the edge at o in ultrasound image: a and b. Suppose we know the normal of the object surface near o, we can draw a plane with the object surface normal through b as the red plane in Figure 4 (b). As we can see this plane intersect with line segment ot which means if o is not the first edge pixel in the ultrasound image from the transducer. Then it is contradict with the fact that o is detected as the first edge from the transducer. So b can not be on the object surface. Similarly we can create a plane through a with object surface normal as the green plane shown in Figure 4 (c). It doesn't intersect with line segment ot. So a should be the true point on the object surface. By applying this logic to every 3D object surface point, we correct errors caused by ultrasound image thickness.



(a) (b) (c)

Fig. 4. 3D position correction

Now we only need to know the object surface normal at point o. It can be estimated by first registering the un-corrected 3D points to the 3D surface model of the object (usually from pre-operative CT or MRI). After registration, we take the normal of the closest point on the surface model to o as the estimated object surface normal. Because we only use this normal to determine which one of a and b is the true object surface point, a rough estimation will work.

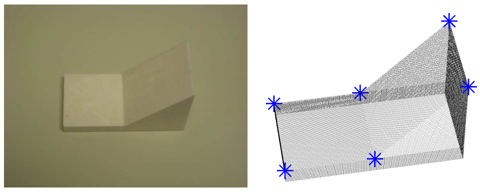
3.2 Registration with Thickness Correction

The registration process using 3D ultrasound catheter with thickness correction can be summarized as the following:

1. Scan the object surface with 3D ultrasound catheter's image plane and reconstruct un-corrected 3D surface points.
2. Register the un-corrected 3D points to the high-resolution pre-operative 3D surface model of the object and estimate object surface normal for every un-corrected 3D surface point o.
3. With thickness information and normal of ultrasound image plane from 3D position sensor in ultrasound catheter, calculate two possible surface points a and b for every un-corrected 3D surface point o.
4. With estimated object surface normal, create two possible object surfaces through a and b and find if they intersect with the line segment ot which is from un-corrected point o to transducer's center t. Keep the one whose surface does not intersect with ot. And it is the corrected 3D surface point.
5. After correction, use the corrected 3D surface points to do a final registration to the 3D object surface model.

4 Experiment and Result

4.1 Test Setup



(a) (b)

Fig. 5. Phantom model in registration test: (a) the model (b) its 3D model

Phantom Model We use a simple shape phantom model as shown in Figure 5 (a). Because its shape only consists of several flat surfaces and is not rotational symmetric, it will not introduce any registration difficulties caused by the shape itself. The 3D surface model is shown in Figure 5 (b).

Registration Error Measurement Most common way to measure registration error is to use the average distance from registered points to their closest surface points. ICP algorithm actually tries to minimize such measurement. The problem is that it is usually smaller than the distance from registered points to their true correspondence on object surface. In this case, such error measurement could be misleading. In this paper we use a separated set of points called evaluation point set whose corresponding points on object surface are known, as shown in Figure 5 (b) the blue stars. During the test, we will first use 3D ultrasound catheter to scan the model to capture surface points for registration. Also we use a catheter whose tip is tracked by a 3D position sensor to touch those blue points as shown in Figure 5 (b) and record their coordinates as our evaluation points. Then we do the registration with only the surface points scanned by ultrasound catheter. After registration, we apply the transformation matrix found by registration to evaluation points and measure how far they are from their corresponding points on the surface model. This is exactly what doctors want to know for medical navigation systems that after registration when they maneuver an instrument to a location as shown by the navigation system, how far it is from the real location they want to go. All the registration error shows in this paper will use such error measurement.

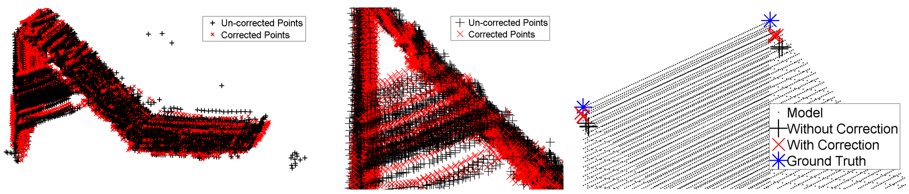
Accuracy Improvement And Intersecting Angles Error caused by ultrasound image plane thickness is related to the intersecting angle of the image plane and the object surface. If the image plane is perpendicular to the object surface (90 degree), there will be no error caused by image thickness. Smaller the intersecting angle is, larger the error will be. To understand how the intersecting angle will affect registration error and how our thickness correction algorithm can help, we will do a series of tests. First we scan the phantom model with ultrasound image plane with various intersecting angles (0-90) and save all the images. Then we sample them to form several subsets of ultrasound images each with a different average intersecting angles.

For example one subset may have many images whose average intersecting angle is 80 degree and another set has an average intersecting angle of 40 degree. We expect that the registration error with un-corrected points from the 80 degree set will have less error than that from the 60 degree set. After thickness correction, they should all have improvements and both sets should have similar errors. The relation among expected registration errors should be:

$$P^{40}_{un-corrected} > P^{80}_{un-corrected} > P^{40}_{corrected} = P^{80}_{corrected} \quad (2)$$

where $P^{x}_{un-corrected}$ means registration error with un-corrected points from a subset whose average intersecting angle is x and $P^{x}_{corrected}$ means registration error with corrected points.

4.2 Result and Analysis



(a) (b) (c)

Fig. 6. Corrected (red x) and un-corrected (black +) surface registration points and result of evaluation points

Figure 6 (a) and (b) shows the overall and zoomed in view of thickness corrected (red x) and un-corrected (black +) surface points. We can see the corrected points have a tighter fit than the un-corrected ones. After registration, we can see the result of evaluation points in Figure 6 (c), the result from corrected points (red x) are closer to ground truth (blue *) than un-corrected points (black +). Full results are shown in Figure 7. X-axis is average intersecting angle. Y-axis is registration error. If we look at the range from 40 to 70 degree, it fits the Equation 2 well. Overall, corrected points always have less error than their un-corrected counterparts. Averagely, with thickness correction, registration error can be reduced by 20.45%. More important, our result shows the algorithm can achieve consistent accuracy independent of intersecting angles. In reality, catheter flexibility and the size of human heart chambers may prevent doctors from scanning with near 90 degree intersecting angles. With our algorithm, it will never be a problem. Thus it makes the registration process even easier.

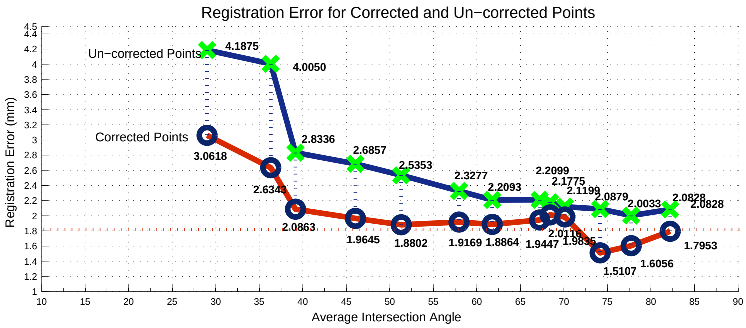


Fig. 7. Registration accuracy and average intersecting angle between image planes and model's surface.

5 Conclusion

Our algorithm can correct reconstruction errors of 3D ultrasound catheter caused by image plane's thickness. It is effective (20% boost on accuracy) and consistent (independent of intersecting angle). Combining our algorithm to systems like [3] will result in a fast and accurate navigation system for minimally invasive surgery.

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